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MASTER

March 1980

DEPARTMENT OF ENERGY AND ENVIRONMENT

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OCEANOGRAPHIC SCIENCES DIVISION

DEPARTMENT OF ENERGY AND ENVIRONMENT
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ABSTRACT

Since inception of oceanographic research at Brookhaven National Laboratory in 1974, over 75 cruises and 150 papers and reports have been completed. In comparison of shelf ecosystems at high, mid, and low latitudes, an understanding of the natural variability of U.S. coastal waters has been derived. Annual carbon and nitrogen budgets suggest that the energy flow is diverted to a pelagic food web in summer-fall and a demersal food web in winter-spring within the Mid-Atlantic Bight. The impact of energy-related perturbations can now be assessed within the context of natural oscillation of the coastal food web.

Over the last 400 years, the human population of the northeast coastal zone has grown from a few Indian settlements to the present megalopolis of 45 million people, housed in an almost continuous urban development from Norfolk, Virginia to Portland, Maine. About 15 million people live just within the coastal counties of the New York Bight from Cape May, New Jersey to Montauk Point, New York. The annual energy consumption of the northeast United States was 13.6×10^{15} BTU's in 1975, with only 2.7×10^{15} BTU's produced in this region; a net energy import of 10.9×10^{15} BTU's was thus required for the northeast, 60% of which was in the form of oil. A combination of $\sim$200 fossil fuel power plants, 20 nulcear plants in operation or under construction, 12 major oil refineries, and 4 LNG terminals (Figure 1) are located within this coastal region through which a great deal of the annual energy supply passes.

Major facilities for construction and resupply of nuclear submarines are located at Norfolk, Virginia, at New London, Connecticut, and at Portsmouth, New Hampshire. Power plants, industrial and military complexes, and other energy-related activities emitting pollutants are often sited in coastal areas because of the proximity of cities, transportation, and available cooling water. The increasing utilization of the northeast coastal shelf for oil drilling, e.g. Georges Bank and the Baltimore Canyon, for continued oil transport, for siting of power plants, for various types of planned and inadvertent waste disposal, as well as for food and recreation, thus requires a careful analysis of the impact of these energy-related activities on the coastal marine ecosystem. The Brookhaven National Laboratory (BNL) oceanographic program was designed to evaluate this impact, with research initiated in 1974.

During 1974, 1.3×10^8 tons of crude petroleum and petroleum products were imported between Hampton Roads, Virginia and Portland, Maine, of which 0.4×10^8 tons was offloaded in storage tanks or refineries along the Hudson and Raritan Rivers. After processing by society and partial conversion to CO_2, a residue of 3×10^5 tons of oil and grease ($\sim$1%) is usually returned each year to waters of the New York Bight through dumping and waste water runoff of the coastal communities in New York and New Jersey. With grounding of the tanker Argo Merchant on Nantucket Shoals during 15 December 1976, however, 2.7×10^4 tons of #6 fuel oil was released to the coastal ecosystem in this single incident, i.e. 30 times the usual daily discharge of oil to the coastal systems. Similarly, a decade earlier on 16 June 1966, the tanker Texaco Massachusetts rammed another tanker Alva Cape in New York Harbor, a cargo of naptha was discharged, and the ensuing explosion claimed 33 lives on the two ships and nearby tugs.

We have come to realize that dilution of these effluents by seawater can no longer be considered a simple or permanent removal process within either the open ocean or nearshore waters. In fact, the continental shelf between Cape Hatteras and Georges Bank, in the Mid-Atlantic Bight, is subject to both atmospheric and coastal input of pollutants in the form of present releases of heavy metals, synthetic chemicals, petroleum hydrocarbons, and radionuclides, as well as in the form of deposits of past urban wastes. During 1951-67, about 34,000 containers of radioactive waste (including the pressure vessel of the Seawolf reactor) were dumped off the northeast coast, while the tragic loss of the Thresher occurred only 300 km off Boston in 1963.

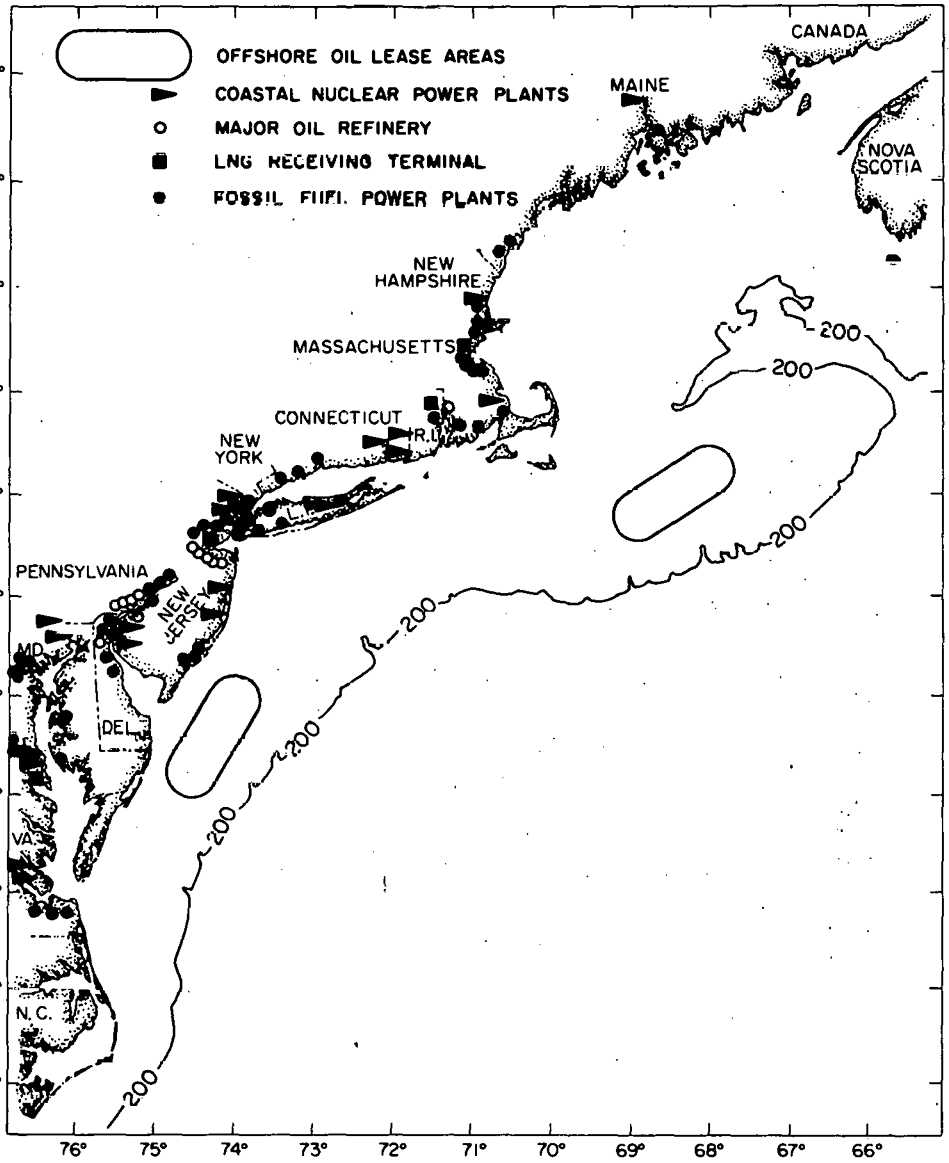

Figure 1. Location of energy-related activities in the Northeast coastal zone.

Overfishing is an additional man-induced stress. The present commercial finfish stocks on the U.S. northeast continental shelf have been reduced by 50% over the last 10 years as a result of heavy fishing by foreign nations and the United States. The recreational yield of finfish and shellfish to residents of the coastal states between Virginia and Maine in 1974 was 0.2×10^6 tons with an expenditure of $360 million within the sport fishing industry. In contrast, the commercial yield to other residents of these states was 0.4×10^6 tons at a value of $303 million in 1977, whereas the peak yield of fish between Cape Hatteras and Nova Scotia was 1.4×10^6 tons, including menhaden, during 1970-73.

Because of natural variability in abundance of organisms in the coastal food web, overfishing, and the release of pollutants to coastal waters, determination of cause and effect within a perturbation of the coastal food web is a difficult matter. For example, the 1976-77 closures of local coastal fisheries can be traced to PCB contamination of the Hudson River and Kepone contamination of the James River. However, it was not possible to detect changes in offshore productivity after a shipload of the pesticide Mopac was discharged at sea in March 1979. Furthermore, the $60 million loss of shellfish industry in 1976, as a result of anoxia off the New Jersey coast, has been attributed to natural interannual oscillations in seasonal changes of the species composition of the food chain rather than pollutant impact.

Knowledge of the movement and dispersive capability of the waters in the northeast continental-shelf region is essential to describing the shelf's ecosystem and the fate of waste discharges or contaminants introduced into its waters. The mechanisms causing water movements along the entire shelf must be understood before the impact of contaminants on biota and water properties can be predicted. This depends upon the ability to explain the finer-scale processes that, in sum, form the larger circulations, including the transient and non-linear events that impair general knowledge and predictive capability.

A unique current meter system was thus developed at BNL to measure the flow of the surface waters, where most of the plant production occurs, in seven experiments at different times of the year south of Long Island between 1975 and 1979. Line-of-sight telemetry was used both to insure recovery of data and to be able to change sampling plans of cruises in response to "real-time" changes in the physical flow field. Subsequently, moored fluorometers to estimate changes in plant biomass, and air-sea interaction buoys to measure wind speed, direction, and stress were added to the current meter system with a capability for data telemetry by satellite.

It was found that the average flow from Georges Bank to Cape Hatteras is $\sim$5 cm sec^{1-} to the southwest along the continental shelf with a transit time for a water parcel of $\sim$1 year. Storms with a wind velocity >10 m sec^{-1} contribute to two-thirds of the net westward water flow and a sediment transport of 1 km $year^{-1}$ during winter, when the average wind speed is 8 m sec^{-1} in January compared to 5 m sec^{-1} in July. The northeastern part of the shelf on Georges Bank and Nantucket Shoals (Figure 2) has tidal currents greater than 55 cm sec^{-1}, which can lead to the same vertical mixing of the water column as from a 13 m sec^{-1} storm. In contrast, the southwestern part of the shelf from New York to Virginia receives river discharge through coastal estuaries in increasing amounts from the Connecticut River to the Chesapeake Bay, which releases 50% of the mean annual runoff of 157 km^3 of fresh water to the Mid-Atlantic Bight.

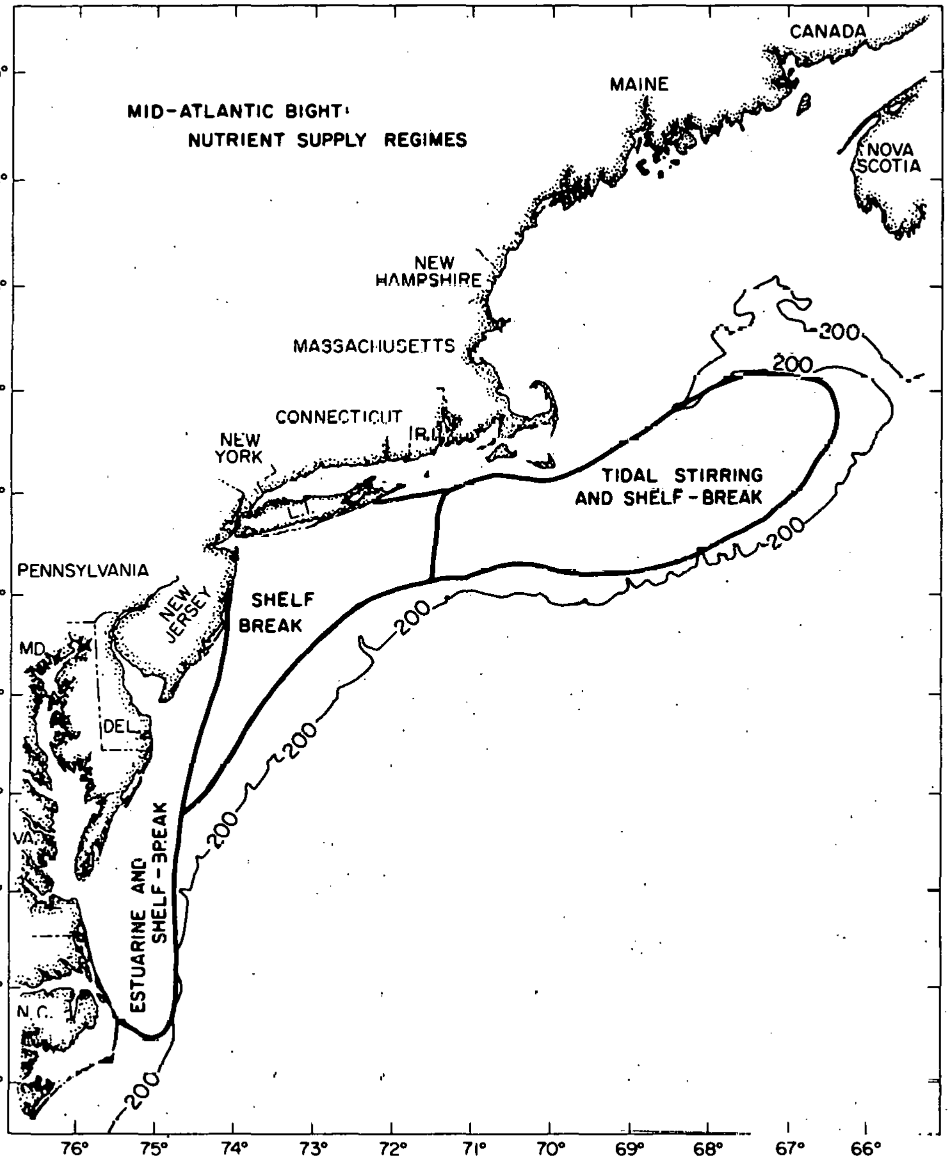

Figure 2. Physical mechanisms for introduction of nutrients to the Northeast continental shelf.

The long period salt balance for the shelf waters is maintained by exchanges across the shelf-break ($\sim$100-200 m depths), with salt gain occurring through onshore subsurface intrusions and freshened water lost offshore both at the surface and through entrainment of shelf water into the Gulf Stream at Cape Hatteras. As much as 75% of the bottom water in the New York Bight is derived from the Gulf of Maine - Georges Bank region, suggesting that an oil spill on Georges Bank, similar to the Campeche Bank spill, would travel south, impacting the New York and Chesapeake Bights in addition to the present pollution input from the estuaries.

Fixation of CO_2 by primary production of plants in marine ecosystems is directly related to the distribution of phytoplankton biomass, the nutrient supply, and light (which limits the rate of growth). The species composition of a patch or bloom of phytoplankton is also tied to light quality and quantity, nutrient level, storm frequency, water column stability, grazing pressure, and mortality factors induced by man's alteration of the marine habitat. In collaboration with other researchers at the Woods Hole Oceanographic Institution, Lamont-Doherty Geological Observatory, State University of New York at Stony Brook, NOAA-National Marine Fisheries Service Laboratories in Massachusetts, Rhode Island, New Jersey, and the NOAA-Atlantic Oceanographic Meteorological Laboratory in Florida, the BNL oceanographic program has conducted 50 cruises on UNOLS and NOAA vessels over the last 5 years to provide data on nutrient fluxes to primary producers and their subsequent utilization by dominant herbivores from Cape Hatteras to Georges Bank. Such information is needed to understand the regulation and possible disruption of carbon flow from primary producers to higher trophic levels.

From analyses of these data we have thus far learned the following: The onshore subsurface transport of salt across the shelf-break provides a major nutrient supply for productivity of the coastal zone. Nitrogen is the most limiting nutrient. About 50% of the nitrogen demand of the annual production of $\sim$250 g C m^{-2} yr^{-1} on the shelf between Montauk Point and Cape May is supplied from onshore flux of nitrate. The rest of the nitrogen used in plant growth within this area is supplied from regenerated ammonium from the excretion of bacterioplankton, zooplankton, and benthos; this second nitrogen supply is more subject to disruption from energy-related activities. As a result of additional nitrogen inputs from tidal mixing and estuarine runoff (Figure 2), the annual primary production is $\sim$ 500 g C m^{-2} yr^{-1} on Georges Bank and within the Hudson River plume. Because of the additional complexity of the other nitrogen sources, however, a detailed analysis of the natural variability of the food web south of Long Island, fed only by the cross-shelf supply of nitrogen, was first studied in an attempt to distinguish natural and man-induced perturbations of the coastal zone.

After the December-January minimum of light in coastal waters, a nearshore February bloom of phytoplankton is first observed in these well-mixed, nutrient-rich winter waters (Figure 3). By March, there is sufficient light for a bloom to take place at mid-shelf with high primary production by large phytoplankton, little grazing loss, and few larval fish. With a decline in storms, increased solar insolation and stratification of the water column, it becomes harder to mix nutrients into the euphotic zone. The spring phytoplankton blooms are found at the shelf-break and then landward of the midshelf area (Figure 4), where nutrient supply is the largest. There is an increased grazing loss, more ichthyoplankton, and a change in phytoplankton species composition from large diatoms to small flagellates, diatoms, and a

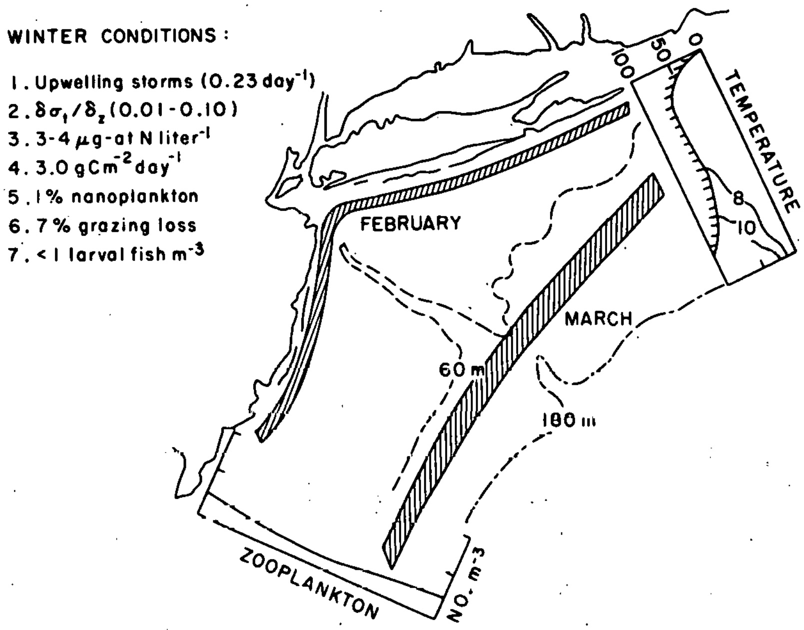

Figure 3. Winter state of the shelf ecosystem.

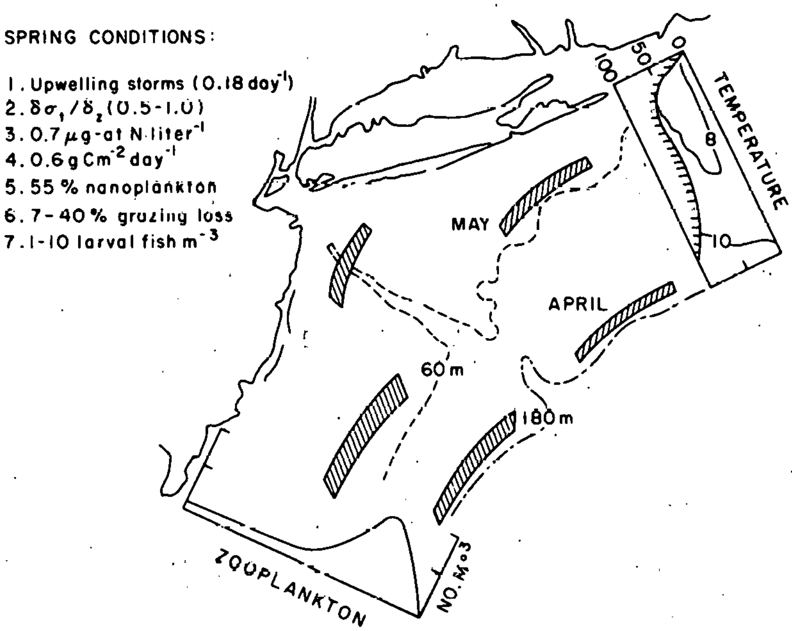

Figure 4. Spring state of the shelf ecosystem.

large dinoflagellate, *Ceratium tripos*. Water column stratification is strongest in summer with the input of nutrients and high chlorophyll areas restricted to within 10 km of the coast (Figure 5). The largest grazing loss to zooplankton and the most larval fish are found at this time of year. Since the amount of organisms and rate of production changes as much as tenfold between season and places within the New York Bight, the impact of a pollutant release would depend on where and when it was released.

From the vast amount of collected data we have been able to construct an annual carbon budget of the coastal food web in the New York Bight (Figure 6). This carbon budget suggests that the flux of particulate matter through the pelagic herbivores and thence pelagic fish occurs mainly in the summer-fall, while carbon flow is directed to the food web leading to demersal fish in winter-spring. The resident time and fate of this organic matter, sinking to the shelf sediments, is important in terms of both dispersal of pollutant energy-related particulates and as an intermediate sink in the global CO_2 cycle. Approximately half of the carbon fixed by the phytoplankton in this region, not including the richer areas of Georges Bank and the Hudson River plume, appears to sink to the bottom, but not be consumed by the benthic community. Since there is little carbon in the sediments of the northeast continental shelf, the organic matter, like fine-grain sediments, may be transported off the shelf to the upper slope where more carbon is found in the sediments. The amount of particulate nitrogen that is apparently exported off the shelf is the amount of dissolved nitrate imported onto the shelf each year, i.e. a mass balance of nitrogen exchange across the shelf-break is maintained.

The major organic carbon sink of the global CO_2 budget may occur on the continental shelves where nitrogen does not limit primary production over a great deal of the year. With a minimum annual shelf primary production of 200 g C m^{-2} yr^{-1}, a total shelf area of the world of 2.6×10^7 km^2, and a 60% ratio of carbon export to production, about 5×10^9 tons C yr^{-1} would be fixed in photosynthesis and 3×10^9 tons C yr^{-1} would be lost to the continental slope from all shelves. In fact, present CO_2 budgets, which contain only physical processes, require an unknown sink of $\sim 3 \times 10^9$ tons C yr^{-1} to account for the missing CO_2 emitted from increased burning of fossil fuel and deforestation, but not observed in the atmosphere or mixed in the deep sea over the last 20 years. Carbon export from the shelves is not a new sink for CO_2, but a neglected one that could be impaired if energy-related pollutants were to disrupt the normal food chain relations of the coastal zone.

It is clear that environmental problems in the coastal ocean occur at the system level of complexity and require a group effort, using systems analysis methodology, for their solution. Systems studies of total marine ecosystems have had to wait, however, for the emergence of adequate technology and sufficient interest in a multidisciplinary group-effort approach to oceanography. In response to DOE concern about the environmental consequences of energy-related activities in the Northeast, the research group of the Oceanographic Sciences Division was specifically assembled at BNL in 1974-75 to study the coastal marine ecosystem in this fashion. Over the last five years, the above large data base was collected by BNL staff and collaborators as input to computer models of the coastal food web, within which natural and man-made perturbations could be examined.

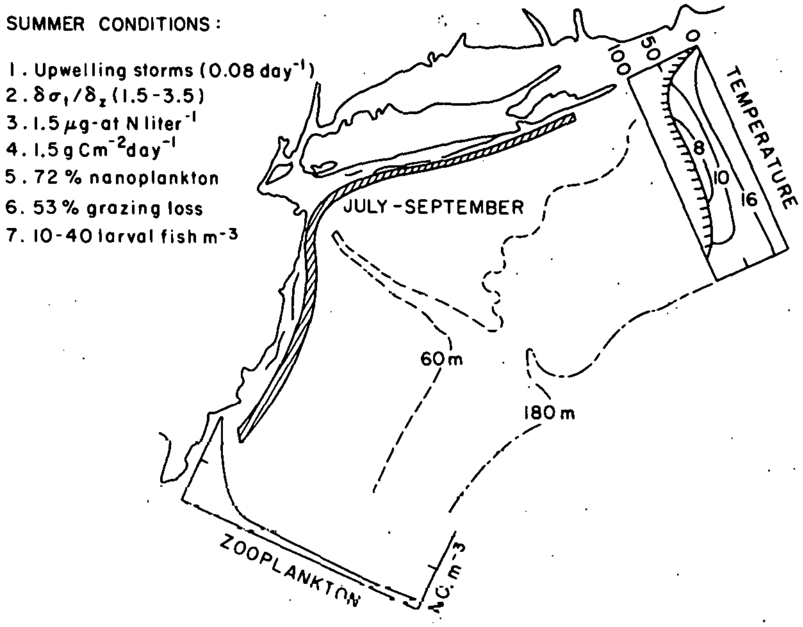

Figure 5. Summer state of the shelf ecosystem.

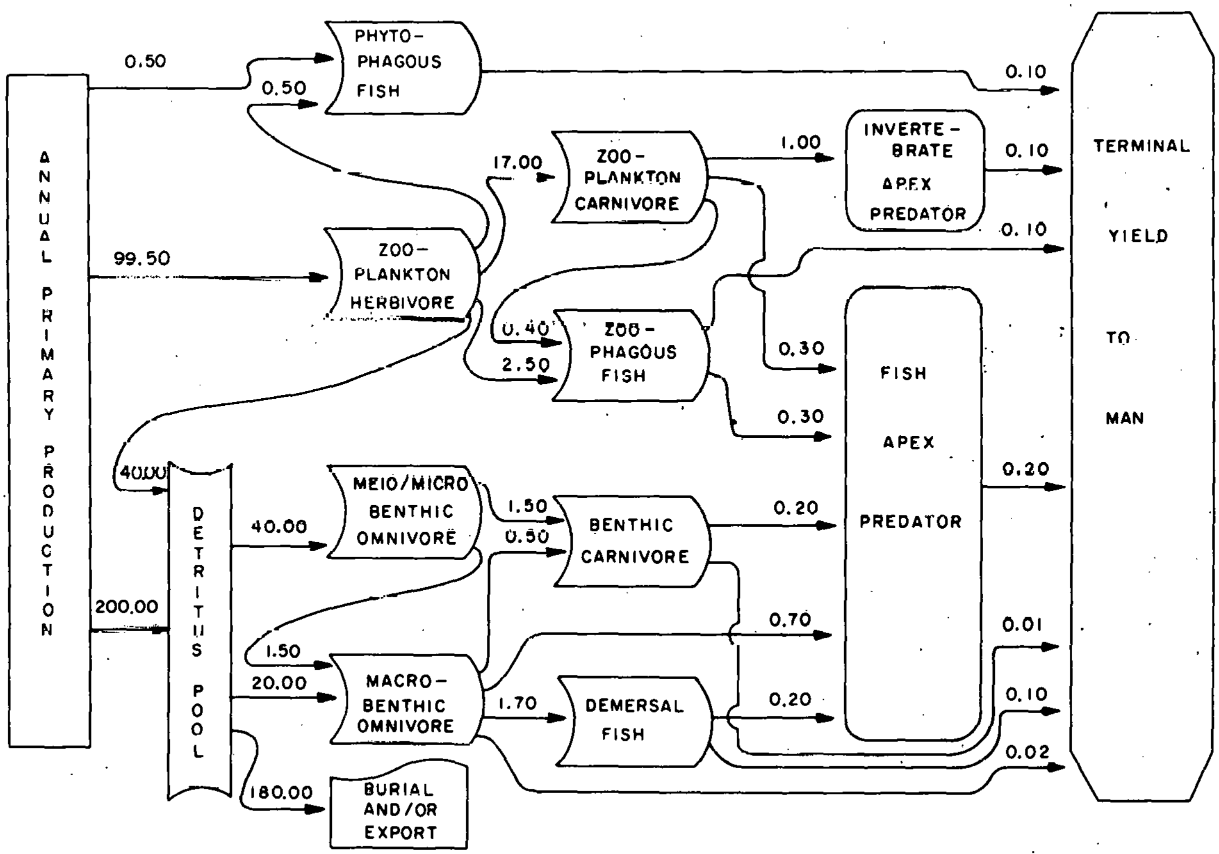

Figure 6. A CARBON BUDGET (g C m^{-2}yr^{-1}) OF YIELD TO MAN ON THE NORTHEAST CONTINENTAL SHELF

In an attempt to quantitatively relate changes in carbon fluxes to variations of the wind forcing, simple models were first constructed of the wind-driven water circulation to separate conservative and non-conservative factors controlling the distribution of biological variables. Our initial effort was a depth-integrated, one-layer description of the barotropic flow, with inclusion of a time-dependent wind stress, bottom topography, and Coriolis force. Under strong wind conditions and a homogeneous water column, i.e. winter in the New York Bight, the model predicts fairly well the surface trajectory of particles. We were able to predict the probability of a winter oil spill reaching Long Island beaches from various offshore locations (Figure 7), as well as the tracks of the Argo Merchant spill in 1976 and of oil discharge from a barge within the Hudson River in 1977.

For summer conditions, a two-layered diagnostic circulation model, which incorporates the density field and current meter data, was then applied to the 1976 anoxic event off New Jersey, where the "normal" summer carbon flow to the pelagic herbivores (Figure 6) was interrupted. In years of mild winters when physical conditions allow early onset of phytoplankton species succession, the slow seasonal build-up of Ceratium tripos populations (Figure 4) represents a large summer carbon pool which is not eaten by the herbivores. Under these food chain conditions, if a steady summer wind regime from the south also favors a current reversal to the north and then accumulation of the C. tripos populations under the Hudson River plume, the oxygen demand of these organisms exceeds the rate of resupply of oxygen to the lower part of the water column, i.e. anoxia occurs. Incorporation of biological terms in the diagnostic circulation model allowed us to simulate the transport and respiration of the C. tripos populations. The predicted subsurface depletion of oxygen in 1976 agrees with observations (Figure 8), suggesting that the cause of anoxia was not anthropogenic energy-related pollutants, but a consequence of normal physical and biological interannual variability of the coastal ecosystem.

Incorporation into an ecosystem model of additional biological and chemical terms to simulate pollutant releases within the coastal zone requires (1) dosage response functions of the organisms to each class of pollutants, (2) a quantitative description of the "normal" food web interaction of the northeast coastal zone, (3) knowledge of where and when the introduced pollutants interact with the coastal food web, and (4) the residence time of dissolved and particulate-associated pollutants in the coastal zone. Through the efforts of a number of federal and state agencies, toxicity levels in terms of median lethal concentrations (LC 50) of metals, pesticides, biofouling agents, industrial chemicals, and petroleum hydrocarbon fractions have been determined for a number of organisms. Through the efforts of the first phase of oceanographic research at BNL, a quantitative description of the food web of the New York Bight is now available in terms of both carbon-nitrogen budgets and an understanding of the natural variability of this system.

The second five-year phase of BNL research is now oriented towards an understanding of the introduction, interaction, and fate of particulate-related pollutants within the Hudson River, Delaware Bay, and Chesapeake Bay, i.e. downstream of the oil refineries and coastal power plants clustered in these areas (Figure 1). Detrital particulate matter, introduced by society at the head of northeast estuaries, tends to sink out within the estuaries, e.g. Long Island Sound, New York Harbor, and Chesapeake Bay, but the dissolved fraction of nutrients and pollutants passes out of the estuary

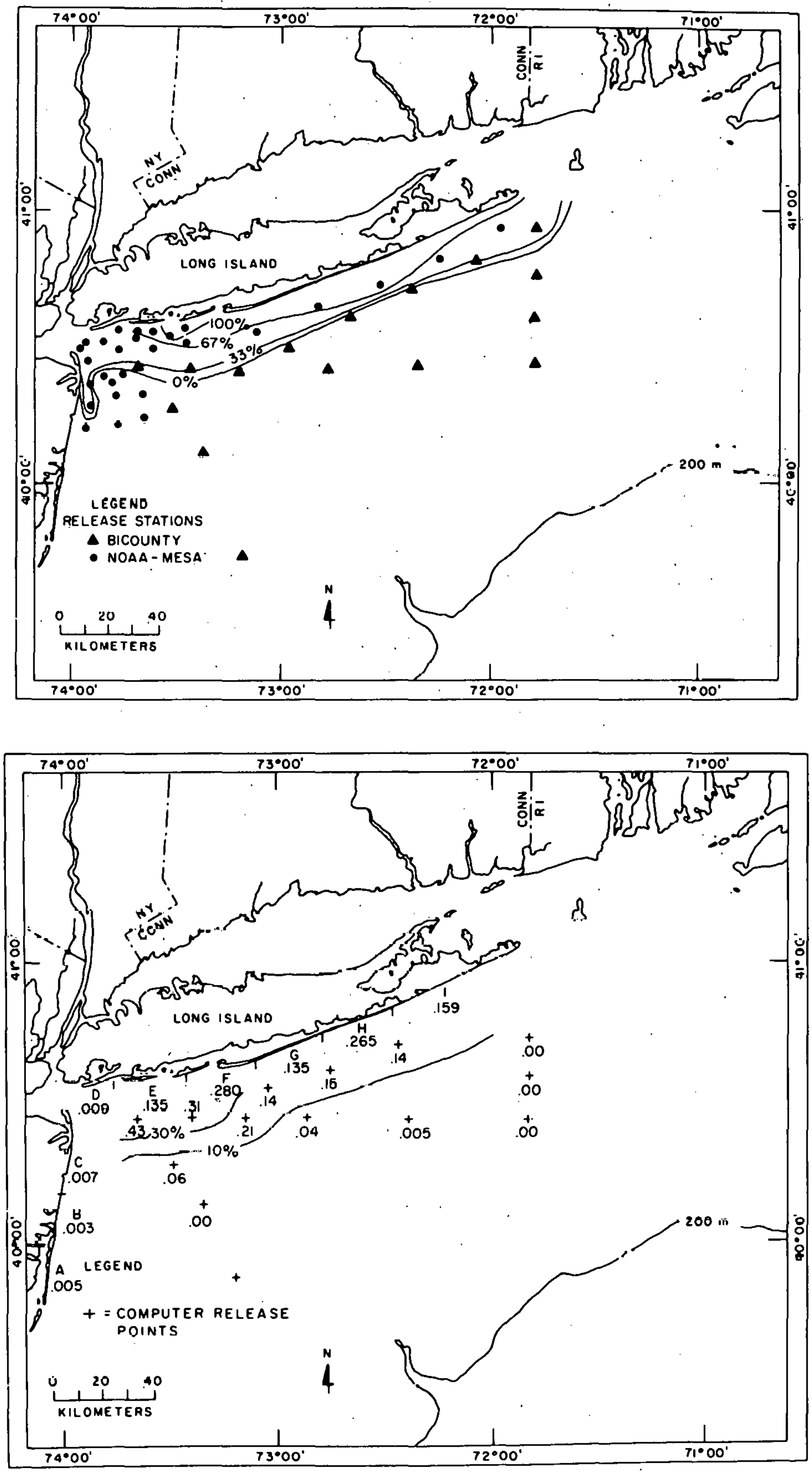

Figure 7. A comparison of drift card trajectories and computed oil spill trajectories.

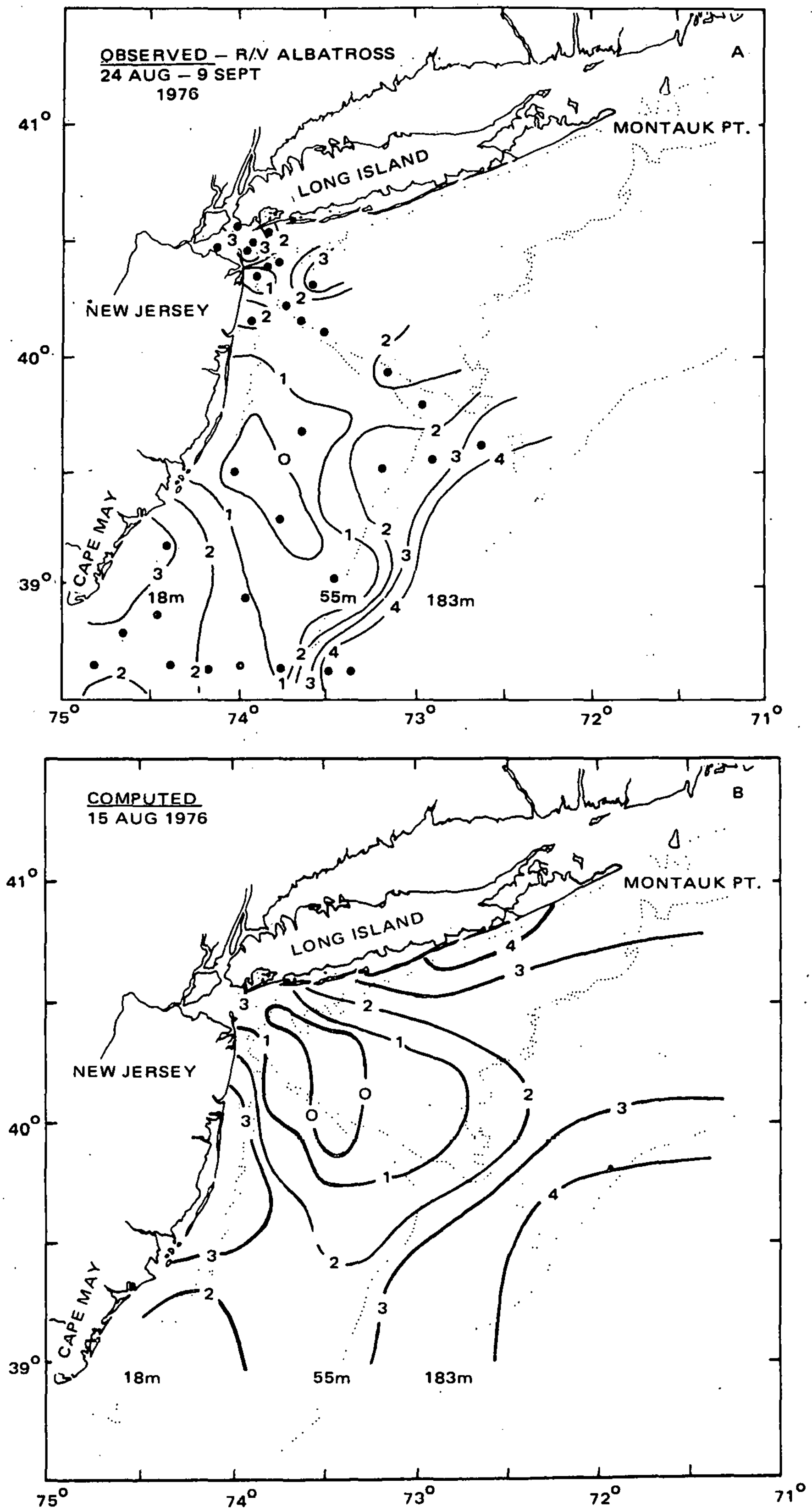

Figure 8. A comparison of observed and computed oxygen concentration near the bottom.

onto the shelf. For example, as a result of burning fossil fuel and river runoff, each year 1 x 10^4 tons of the toxic heavy metals, cadmium, mercury, lead, and copper are released just to the New York Bight; the concentration of cadmium in estuarine discharge is close to the limits set by EPA.

In the process of consuming the estuarine input of nutrients, the nearshore phytoplankton can also assimilate these heavy metals, accumulate them as much as 40,000-fold for copper and lead, and pass this material up the food chain. Discharges of mercury induced Minimata disease and cadmium has led to Itai itai disease in Japan, while an abalone kill off California was attributed to copper pollution from the condensors of a coastal power plant. There is some question about whether chlorinated hydrocarbons are just absorbed or bioaccumulated by marine organisms and how long petrochemicals are toxic in the coastal zone, but at present, the trajectory of these pollutant-related particles within the northeast shelf ecosystem is not understood. Over the next five years, we thus hope to specify how much of the energy-related pollutants leave these estuaries, how much is retained on the shelf, and how much is exported to the slope. From this information we will identify specific areas within the coastal zone that are likely to be most sensitive to energy-related pollutants and we will initiate field effects studies in these areas.

In addition to the major research emphasis on our Atlantic Coastal Ecosystem (ACE) studies of the Mid-Atlantic Bight funded by the Department of Energy, comparative studies have also been made over the last 5 years of the food chain dynamics of both low latitude upwelling ecosystems and high latitude tidally-driven diffusive ecosystems. The demise of the Peruvian anchovy has been studied in six cruises at 5-15°S latitude between 1976-78 within the Coastal Upwelling Ecosystems Analysis (CUEA) program under the auspices of the International Decade of Ocean Exploration (IDOE), National Science Foundation. With support from the Division of Polar Programs, NSF, we have also studied, in the Processes and Resources of the Bering Sea (PROBES) program, the partition of carbon flow leading to year class success of Alaska pollock across the wide shelf of the Bering Sea at 50-60°N latitude in 10 cruises between 1976-79. The results of our 75 cruises and 7 deployments of moored instruments within these three research programs (ACE, CUEA, and PROBES) are described in the following publications.

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